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Dated 28 January 2003

Patents Form 1/77

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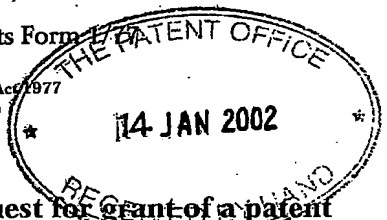

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Cardiff Road
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NP9 1RH

1. Your reference — P33278GB/GVR

2. Patent application number *(The Patent Office will fill in this part)* — 0200744.1

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

Imperial College of Science, Technology & Medicine
47 Prince's Gate
Exhibition Road
London SW7 2QA

Patents ADP number *(if you know it)* 4050744002

If the applicant is a corporate body, give the country/state of its incorporation — United Kingdom

4. Title of the invention

PREPARATION OF NANOPARTICLES

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

Kilburn & Strode
20 Red Lion Street
London
WC1R 4PJ

Patents ADP number *(if you know it)* 125001

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*

a) any applicant named in part 3 is not an inventor, or
b) there is an inventor who is not named as an applicant, or
c) any named applicant is a corporate body.
See note (d))

YES

Patents Form 1/77

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	Continuation sheets of this form
Description	7
Claim *(s)*	1
Abstract	-
Drawing *(s)*	3 + 3

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Priority documents	-
Translations of priority documents	-
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	-
Request for preliminary examination and search *(Patents Form 9/77)*	-
Request for substantive examination *(Patents Form 10/77)*	-
Any other documents *(please specify)*	-

11. I/We request the grant of a patent on the basis of this application.

Signature [signature] Date 14 Jan 2002

12. Name and daytime telephone number of person to contact in the United Kingdom

Gwilym Roberts
Tel: 020 7539 4200

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PREPARATION OF NANOPARTICLES

The present invention provides a method for the production of nanoparticles using a continuous flow miniaturised reaction vessel.

Nanocrystalline semiconductors are of considerable scientific and commercial interest owing to their tuneable optical and electronic properties, and their potential applications in a wide range of electronic devices. Physical characteristics of nanocrystallites are determined primarily by spatial confinement effects with properties such as the optical band gap often differing considerably from the bulk semiconductor. As these properties are ultimately determined by the physical size and shape of the crystallites, there is considerable interest in processing routes that yield nanoparticles of well-defined size.

Known techniques for producing near monodisperse nanoparticles are relatively complex. Usually, the nanoparticles are produced in two stages: a poly-disperse sample of nanoparticles is first obtained using standard synthetic routes. Isolation of nanoparticles of a given particle size can then be performed by means of repeated recrystallisations. This method is time consuming due to the need for repeated recrystallisations and results in low product yields. In addition, this method is not amenable to industrial or commercial scale up. This approach is therefore suitable only for the production of nanoparticles in a research environment.

The first aspect of the invention provides a method for the preparation of nanoparticles using a continuous flow miniaturised reaction system.

The continuous flow format utilises a miniature reaction vessel wherein products are continuously extracted and reactants continuously replenished. The present invention utilises a microfluidic reaction vessel wherein the reactant and product samples are transported and manipulated through one or more channels wherein the channels have

a cross-section of from approximately 1000 microns to approximately 0.1 microns.

As previously discussed, the present invention involves the use of a miniature reaction vessel. For the present invention, the reaction vessel has a reaction volume of between 1×10^{-5} to 1×10^{-11} litres preferably 1×10^{-6} to 1×10^{-10} litre, more preferably 1×10^{-7} to 1×10^{-9} litre. It will be appreciated that the actual volume of the reaction vessel may be greater than the reaction volume utilised for the production of nanoparticles. For example, the reaction vessel may have a total volume of 5×10^{-7} litres, while a reaction volume of 1×10^{-8} litres or above is used.

The reduced reaction volume of the reaction vessel allows;

- Rapid mixing of the reactants (via a diffusive process)
- Chemical homogeneity through the reaction volume; and
- Temperature homogeneity through the reaction volume.

Since any variations in local conditions are liable to cause variations in crystalline size, this allows the production of nanoparticles of uniform size and chemical composition.

The present invention therefore provides a method for preparing monodisperse nanoparticles by a direct one-stage process. This method provides nanoparticles of a defined size due to the uniform temperature and chemical homogeneity within the reaction vessel without need for further isolation by recrystallisation. This technique is well suited to commercial or industrial production of nanoparticles as the nanoparticles are directly isolated from the production method without the need for further isolation or purification (for example by recrystallisation).

The continuous flow system of the invention provides nanoparticles in sufficient quantities for commercial and industrial use. The continuous flow system allows the

constant supply of reactants and the constant removal of product. It is therefore possible to run the continuous flow system in a constant manner or for specified periods of time to obtain the required yield of nanoparticles. The continuous flow system also allows recycling of unreacted or partially unreacted starting materials into the reaction vessel to increase the yield and efficiency of the reaction method. Thus it will be appreciated that while the instantaneous reaction volume of the reaction vessel may be small, the volume of the reactants and ultimately product passing through the reaction vessel may be significant. In addition, two or more reaction vessels can be connected in parallel and provided with the reactants. The number of reaction vessels connected in parallel or the number of connected reaction vessels supplied with reactants can be varied depending on the quantity of nanoparticles required.

The continuous flow system allows the constant recovery of product, as it is not necessary to halt the production to isolate or purify the reaction mixture. It will be appreciated however that the recovered product may undergo purification as required. The present invention therefore provides a method for the production of nanoparticles which is more time efficient, capable of commercial and/or industrial application and which provides nanoparticles in high yield.

The precise control of the reactants and product within the reaction vessel allows the interruption of chemical reactions and allows the isolation of a particular nanoparticle size as required. Thus the present invention provides a method for the preparation of a nanoparticle of a well-defined size. The ability to provide nanoparticles of a defined size is of particular importance for the use of the nanoparticles in electronic devices, as the optical properties of the nanoparticles is influenced by their size.

For the purposes of this invention, the term "monodisperse" relates to a narrow distribution of particle diameters within a population of nanoparticles. It will be appreciated that the operational definition of narrow will be dependent on the precise application but will typically relate to a size distribution with a variance of up to

±20%, preferably a size distribution with a variance of up to ±10%, more preferably with a variance of around ±2%.

The method of the first aspect can be used to produce nanoparticles of varying chemical compositions. Examples of such nanoparticles include cadmium sulphide, cadmium selenide and zinc sulphide.

In a second aspect, the present invention further provides a nanoparticle as produced by the method of the first aspect.

A third aspect of the present invention provides a nanoparticle production device comprising one or more inlets, a reaction chamber and one or more outlets. For the purposes of this invention, the device can comprise two or more reaction chambers connected in parallel supplied by one or more inlets and one or more outlets.

The invention may be put into practice in various ways and a number of specific embodiments will be described by way of example to illustrate the invention with reference to the accompanying drawings, in which:

Figure 1 shows a schematic representation of a continuous flow method in which reactants are continuously supplied to a reaction chamber and the resulting product is continuously removed therefrom.

Figure 2 shows a schematic representation of a continuous flow method in which the reactants are recycled back into the reaction vessel.

Figure 3 shows the central portion of a micromixer chip wherein two inlet flows containing reactants are split into 16 partial flows (one inlet arrives from a lower layer (not shown)). After mixing the channels are then sequentially recombined in a reverse

network until all partial flows are united in one broad outlet channel.

In order to provide nanoparticles of uniform distribution, it is necessary to maintain the chemical homogeneity of the reaction mixtures within the reaction vessel. This is particularly important for reactions wherein the rate of reaction is of the same order or much shorter than the mixing time of the reactants. In a preferred feature of the first aspect, the miniature reaction vessel is fitted with a fast micromixer such as a continuous flow micromixer as described below.

Referring to Fig. 1, the continuous flow micromixer 10 comprises two inlet flows 12, 14 (each containing one of the reactants) split into a series of separate multichannel streams 20 (shown in more detail in Fig. 3) (16 partial flows) before bringing them back into final contact. As the diffusion time of the reactants which in the stream is proportional to the diffusion distance, splitting each reagent stream into n substreams of similar width decreases mixing times by a factor n^2. After mixing, the channels are then sequentially combined in a reverse network 22 until all partial flows are united in one broad outlet channel 24. As shown in Fig. 2, unreacted or partially reacted reactants can be recycled back into the reaction chamber 26 via outlets 28,30.

In order to provide monodisperse nanoparticles, it is necessary to prevent coalescence of the nanoparticles during and after their formation. This is achieved by isolation of the nanoparticles from the reaction mixture. This prevents coalescence of the newly formed nanoparticles to form larger crystallites. Monodisperse nanoparticles can also be obtained by stabilising the nanoparticles, for example by the addition of one or more stabilising agents via an additional flow channel or by exposing the isolated nanoparticles to one or more stabilising agents. In one embodiment of the present invention a further chemical species is added to the reaction mixture to stabilise the formed nanoparticles. Examples of such chemical species include sodium polyphosphate, tributylphoshine oxide, pyridine, octanethiol and thiourea. It is also possible to prevent coalescence and hence polydispersity of the nanoparticles by

increasing the flow rates of the reactants into and through the reaction vessel. For the purposes of the present invention reactants are provided into and through the reaction vessel at a flow rate of 10nL/min to 5ml/min, preferably up to 2ml/min. More preferably reactants are provided out at volumetric flow rates of 10 microlitres/min to 500 microlitres/min.

The present invention provides nanoparticles of uniform and defined size. Such nanoparticles can be used as optical moieties in for example nanocrystalline semiconductors. The composition of the nanoparticles is not limited and can include cadmium sulphide, cadmium selenide or zinc sulphide.

The reactants for the present invention can be carried out in aqueous or organic solvents. It will be appreciated that the reaction vessel should be selected for its compatibility with the solvent of the reaction (i.e. aqueous reaction solvents allow the use of plastic reaction vessels while some organic solvents will require the use of quartz, metallic or glass reaction vessels).

The present invention will now be described with reference to the following non-limiting example.

EXAMPLE

CdS nanoparticles were obtained by directly mixing $4x10^{-4}$ aqueous solutions of $Cd(NO_3)_2$ $4H_2O$ and Na_2S (Mahtab R.; Rogers J. P.; Singleton C. P.; Murphy C. J.; Am. Chem. Soc. 1996, 118, 7028-7032). To aid stabilisation of the resulting nanoparticles, an equal quantity of sodium polyphosphate was added to the cadmium nitrate solution prior to mixing. A syringe pump was used to deliver the reagents into the microfluidic channel network at various flow rates (10-300 μL/min). The outlet flow from the distributive mixer chip was coupled to a quartz flow cell (10 mm

pathlength) and absorption spectra were obtained using a Perkin-Elmer, Lambda 15 UV-Vis spectrometer.

CLAIMS

1. A method of producing nanoparticles using a continuous flow miniaturised reaction vessel.

2. A method as claimed in claim 1 wherein the reaction volume of the reaction vessel is from 1×10^{-5} to 1×10^{-11} litres.

3. A method as claimed in claims 1 or 2 wherein the nanoparticles produced by the method are monodisperse.

4. A method as claimed in any one of claims 1 to 3 for the production of cadmium sulphide nanoparticles comprising combining an aqueous solution of a cadmium salt and a sulphide salt.

5. A method as claimed in any one of claims 1 to 4 characterised in that a reactant is continuously supplied to the reaction vessel and the nanoparticles produced thereby continuously removed therefrom.

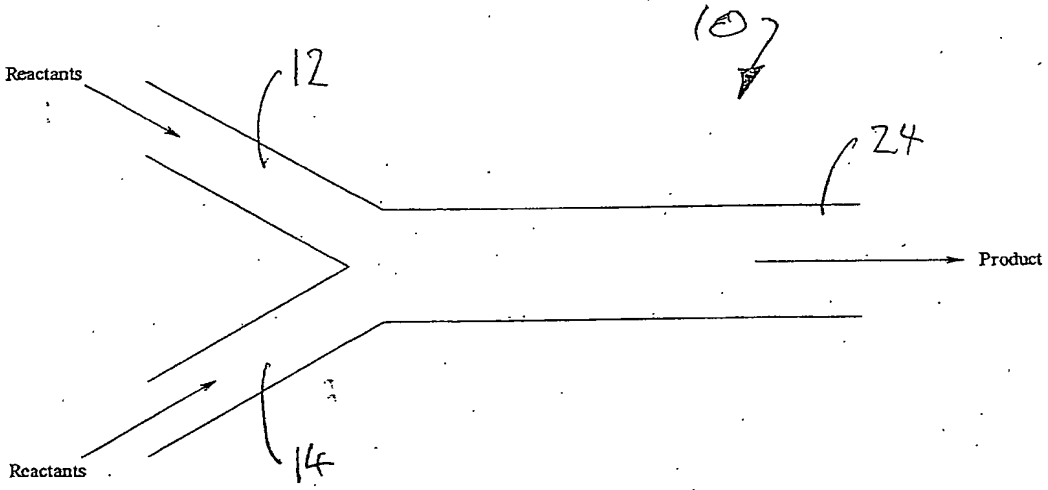
6. A nanoparticle produced by the method of any one of claims 1 to 5.

7. A nanoparticle production device comprising one or more inlets, a reaction chamber and one or more outlets.

8. A method as substantially hereinbefore discussed with reference to or as shown in the examples.

9. A nanoparticle production device as substantially hereinbefore discussed with reference to or as shown in the drawings.

Figure 1



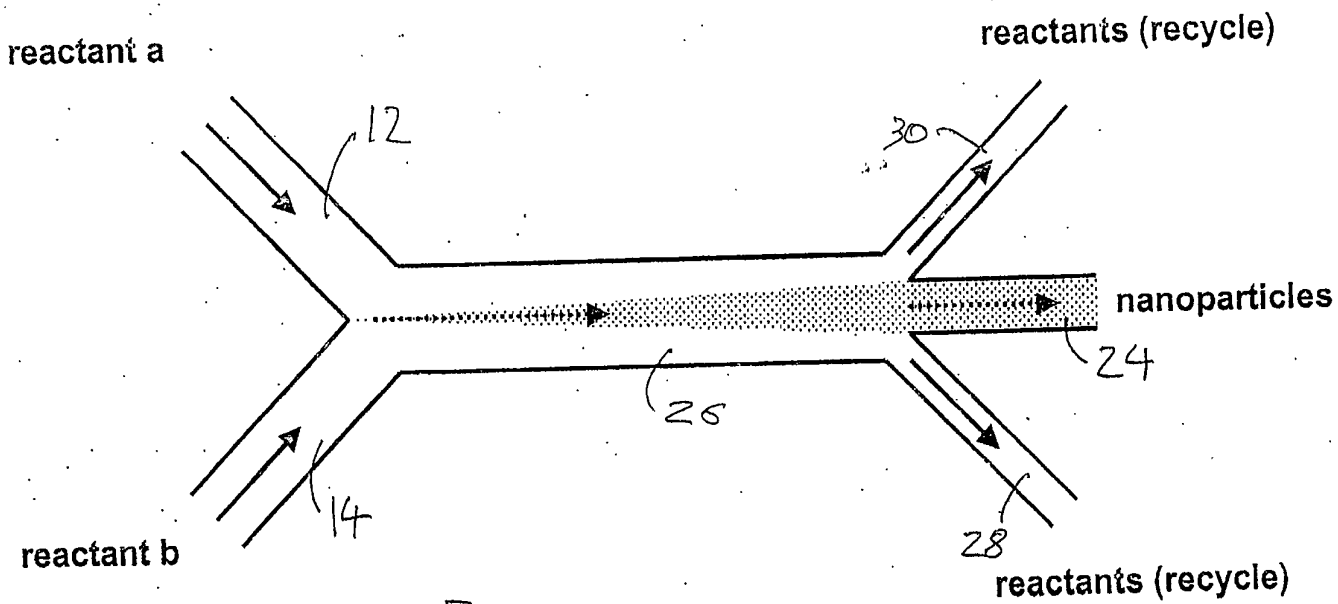

reactant a
reactants (recycle)
12
30
nanoparticles
24
26
14
28
reactant b
reactants (recycle)

Fig. 2

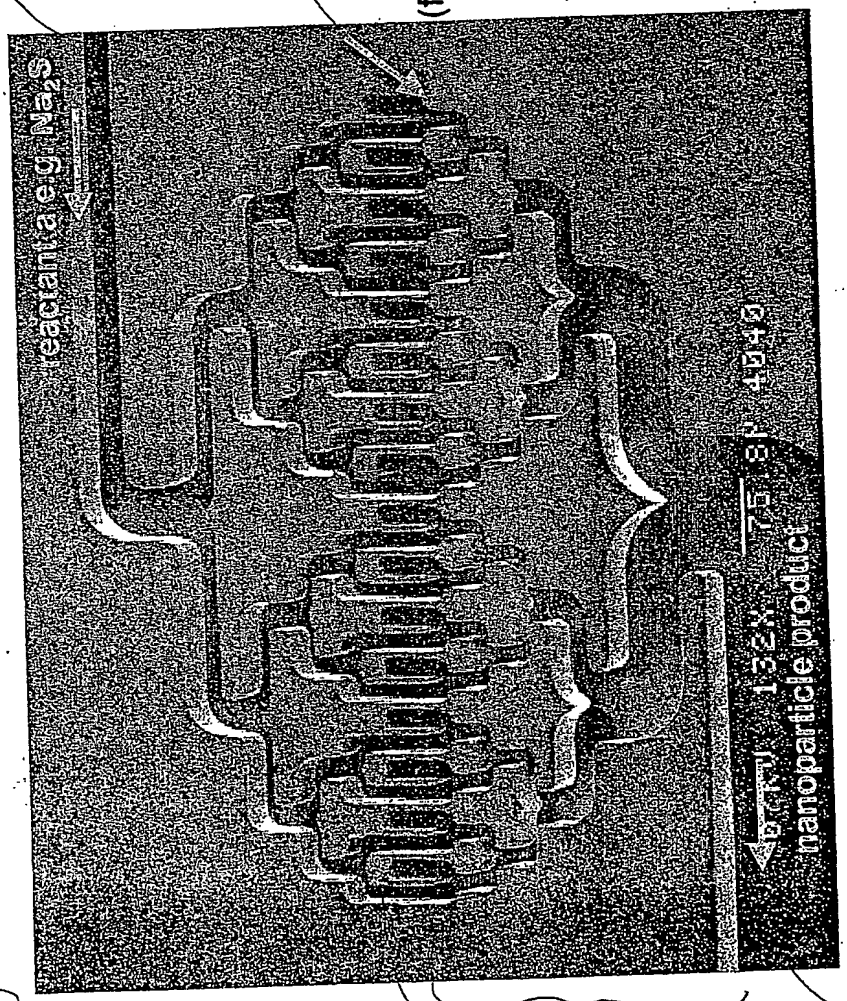


Fig. 3

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